Short and long scale regimes of horizontal flare system exploitation in permafrost

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Abstract

A mathematical model, numerical algorithm and program code for simulation thermal changes in permafrost as a result of operation of a horizontal flare system in northern oil and gas field are presented. In the model the most significant climatic and physical factors are taken into account such as solar radiation, determined by specific geographical location, heterogeneous structure of frozen soil, seasonal fluctuations in air temperature, and freezing and thawing of the upper soil layer. Results of computing are presented.

1 Processes in Permafrost

Oil and gas production has a significant effect on permafrost due to heat from tubes with oil in the wells leads to thawing. Permafrost degradation leads to significant difficulties in the construction and operation of various engineering structures, some of which are already in emergency condition. This problem is compounded by processes of global warming [1] because of request to ensure reliability of the conservation status of frozen soils during the construction phase. In this paper, for simulation of heat distribution from wells and other facilities in permafrost a mathematical model is proposed that takes into account not only climatic(seasonal changes in temperature and intensity of solar radiation due to geographical location of the area) and physical factors (different thermal characteristics of inhomogeneous soil changing over time), but also engineering features of technical systems.

One type of thermal influence is gas flaring in the normal and emergency modes. To reduce the thermal effect and the permafrost distruction there used different insulation matherials and flare pads. Additionally, it is necessary take into account and regulate the mode and capacity of the heat flow from the gas torch.

To solve this problem, it is possible to use a mathematical simulation. Choosing an adequate mathematical model of heat propagation in nonuniform frozen soil, taking into account most significant factors, and carying out neerical experiments is practicably analize different long and short scale modes of a flare system exploitation and choose the most safe and reliable. This is an urgent task for oil and gas industry and construction in permafrost areas.

According to the papers [2, 3] a mathematical model is suggested for long-time forecasting of impacts of development and exploitation of a flare pad located in areas of permafrost.

In [4] is considered a vertical flare system. To simulate influence of a vertical flare as a rule a radiation heat transfer model is used on the soil surface. The height of the flame in a horizontal flare system is lower, so that

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the surface heating is stronger, and on the upper boundary we may assume a fixed temperature.

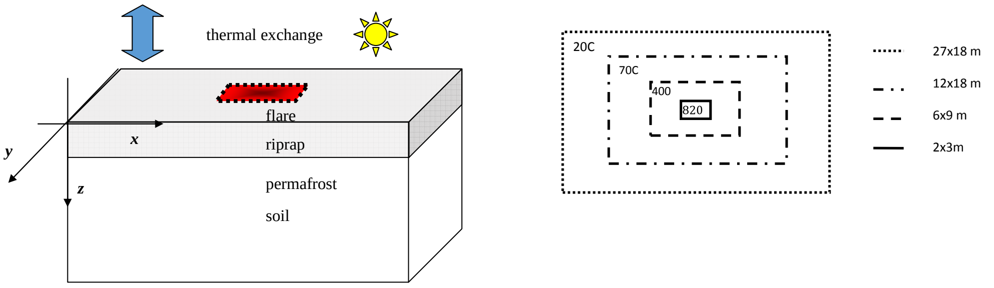
Optimization of exploitation of productive wells in permafrost area are considered [5, 6]. Operating modes of production wells are selected in such a way to reduce the thermal effect of hot oil on the permafrost, and in case of shut-in reverse to slow freezing of engineering constructions. In this paper short and long continued operation of the flare system and simulated the effect of different thermal cycles on the ground are considered.

2 Mathematical model

Simulation of unsteady three-dimensional thermal fields, such as oil and gas fields (the well pads) located in the area of permafrost, is required to take into account the different climatic, physical and technological factors.

The first group of factors is related with solar radiation, seasonal changes in air temperature, resulting a periodic thawing (freezing) of soil, and possible snow layer. The second group factors includes parameters of soil: thermal, dependent with humidity, structure and temperature. The third group of factors are the possible source of heat as production and injection wells, flare systems, pipelines, foundations of buildings, etc. In addition, it is necessary to take into account parameters of used thermal insulation [7] and possible devices used for thermal stabilization (cooling) of the soil such as seasonal cooling devices, as in [5].

We consider a horizontal flare, which is simulated by a heat source on the surface of the permafrost soil (fig. 1). The initial temperature distribution in the soil is presented in fig. 2. The basic thermal parameters of soil are presented in Table 1. In fig. 3 monthly averages air temperature and solar radiation through a year used for simulation the annual temperature cycle in the soil are shown.



(a) (b)

Figure 1: (a) — considered area, (b) — temperature distribution in flare platform.

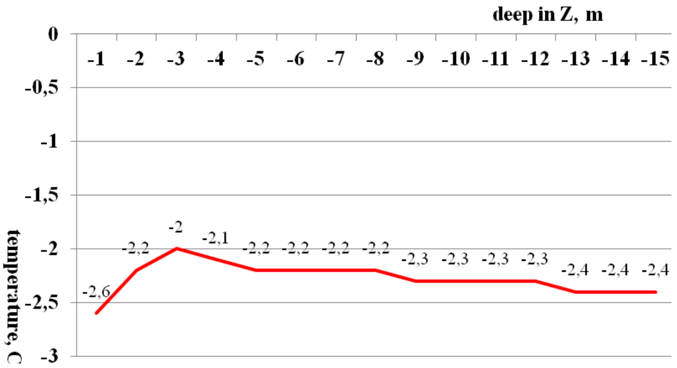


Figure 2: Initial temperature in a frozen soil.

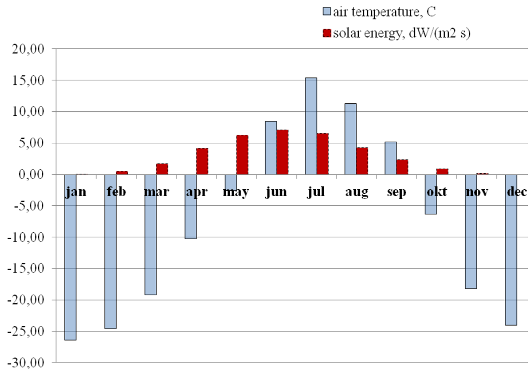


Figure 3: Average air temperature and solar radiation by months.

2.1 Basic Equations

Simulation of processes of heat distribution is reduced to solution of three-dimensional diffusivity equation with non-uniform coefficients including localized heat of phase transition — an approach to solve the problem of Stefan type, without the explicit separation of the phase transition in Ω (fig. 1). The equation has the form

$$\rho\big(c_\nu(T) + k\delta(T - T^*)\big)\frac{\partial T}{\partial t} = \nabla\left(\lambda(T)\nabla T\right), \tag{1}$$

with initial condition

$$T(0, x, y, z) = T_0(x, y, z). \tag{2}$$

Here ρ is density $[kg/m^3]$, T^* is temperature of phase transition $[K]$,

$$c_\nu(T) = \begin{cases} c_1(x,y,z), & T < T^*, \\ c_2(x,y,z), & T > T^*, \end{cases} \text{ is specific heat [J/kg K]},$$

$$\lambda(T) = \begin{cases} \lambda_1(x,y,z), & T < T^*, \\ \lambda_2(x,y,z), & T > T^*, \end{cases} \text{ is thermal conductivity coefficient [W/m K]},$$

$k = k(x, y, z)$ is specific heat of phase transition, δ is Dirac delta function.

Table 1: Basic thermal parameters of riprap layers and soil

	Layers of riprap and soil	Thermal conductivity, W/(m K)		Volumetric heat, kJ/(m^3 K)		Heat of phaze transition, kJ/(m^3 K)	Temperature of phaze transition, C
		frozen	melted	frozen	melted		
1.	concrete slab 0-0.15 m.	1.93	1.57	2150.0	3490.0	141504.0	0.0
2.	breakstone 0.15-0.25 m.	1.75	1.63	2160.0	2630.0	83616.0	-0.8
3.	sand 0.25-2.35 m.	1.83	1.39	1536.0	1983.0	69505.8	-0.1
4.	soil 2.35-10.35 .	1.89	1.68	2200.0	2780.0	90983.7	-0.8
5.	soil 10.35-40.0 .	2.21	1.75	2350.0	2750.0	64461.7	-0.8

2.2 Initial and Boundary Conditions

The computational domain is a three-dimensional box Ω, where x and y axes are parallel to the ground surface and the z axis is directed downward (fig 1a). We assume that the size of the box Ω is defined by positive numbers L_x, L_y, L_z: $-L_x \le x \le L_x$, $-L_y \le y \le L_y$, $-L_z \le z \le 0$.

The flare platform is simulated by a region of fixed temperature in a upper boundary (fig 1b). Balance of heat fluxes at the surface $z = 0$ outside of the flare platform is defined by corresponding nonlinear boundary conditions

$$\gamma q + b(T_{air} - T(x,y,0,t)) = \varepsilon\sigma(T^4(x,y,0,t) - T^4_{air}) + \lambda\frac{\partial T(x,y,0,t)}{\partial z}. \tag{3}$$

Nonlinear boundary conditions of fourth degree is often used for simulations of process where there is a heat exchange as solar radiation or other type of heatet surfaces interaction, for example, in [8].

To determine the parameters in boundary condition (3), an iterative algorithm is developed that takes into account the geographic coordinates of considered area, lithology of soil and other features of the selected location.

In condition (3) values of intensity of solar radiation and seasonal changes in air temperature are obtained by weather stations or on the base of an open climate data for a flare system to be simulated location. Fig. 2 shows the data for the considered field.

The others parameters in condition (3) are determined as a result of geophysical research of oil and gas field. Fig. 2 shows temperature distribution in an exploratory well. Applying the developed iterative algorithm [5, 7] to define some of the parameters in nonlinear boundary condition (3) it is possible to identify them so that the temperature distribution in the soil found as a solution of equation (1)–(3) to be periodically repeated over the next few years, that allows to implicitly take into account different climate and natural features of the considered geographical location.

At the boundaries of the computational domain the boundary conditions are given

$$\left.\frac{\partial T}{\partial x}\right|_{x=\pm L_x} = \left.\frac{\partial T}{\partial y}\right|_{y=\pm L_y} = 0, \quad \left.\frac{\partial T}{\partial z}\right|_{z=-L_z} = \gamma. \tag{4}$$

In (4) γ is a positive number, corresponding to a geothermal flux value. As a rule γ is a small number and it is possible to be set zero in calculations.

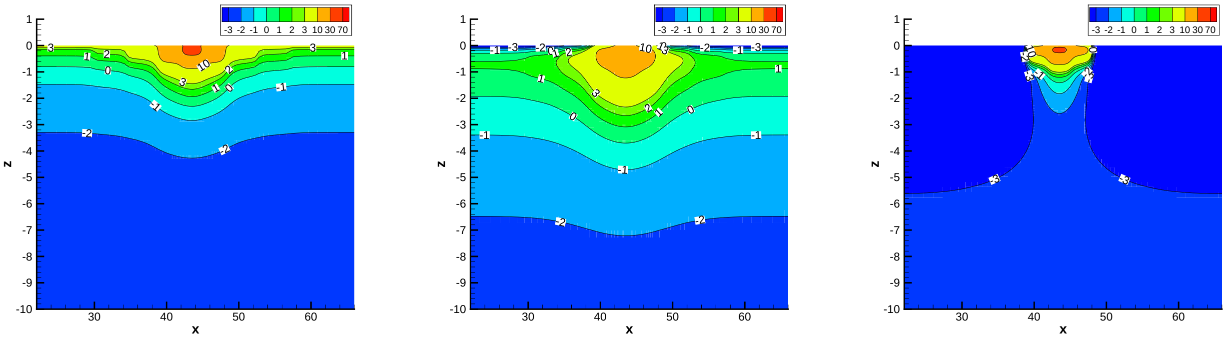
2.3 Methods of Solutions

Numerical methods of solving problems are the most effective and universal method of research for models considered in this paper. A large number of works is devoted to development of difference methods for solving boundary value problems for the heat equation To solve (1)–(4) a finite–difference method is used.

At present there are the following difference methods for solving Stefan type problems: the method of front localization by the difference grid node, the method of front straightening, the method of smoothing coefficients and schemas of through computation [9]. The method of front localization in the mesh node is used only for one-dimensional single-front problems and method of front straightening for the multi-front problems. A basic feature of these methods is that the difference schemes are constructed with explicit separation of the front of phase transformation. It should be noted that the methods with explicit separation of unknown boundary of the phase transformation for the case of cyclic temperature changes on the boundary are not suitable, because the number of non-monotonically moving fronts may be more than one, and some of them may merge with each other or disappear.

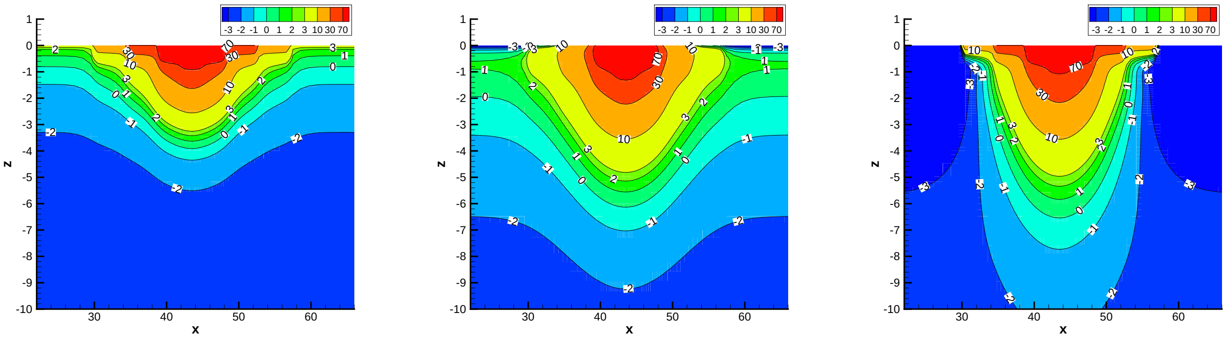
In [10] an effective scheme of through computations is developed with smoothing of discontinuous coefficients in the equation of thermal conductivity by temperature in the neighborhood of the phase transformation. Through calculation scheme is characterized by that the boundary of phase separation is explicitly not allocated, and the homogeneous difference schemes may be used. The heat of phase transformation is introduced with using the Dirac δ-function as a concentrated heat of phase transition in the specific heat ratio. Thus obtained discontinuous function then "shared" with respect to temperature, and does not depend on the number of measurements and phases. Collocation and least residuals method is also used for such equations [11].

With using these ideas [9, 10], to solve problem (1)–(4) in three-dimensional box a finite difference method is used with splitting by the spatial variables and taking into account the inner boundaries Ω_i. Solvability of the same difference problems approximating (1)–(4) is proved in [12, 13].



june october march

Figure 4: I operating mode. Temperature field under flare platform on june, october, and march.



june october march

Figure 5: II operating mode. Temperature field under flare platform on june, october, and march.

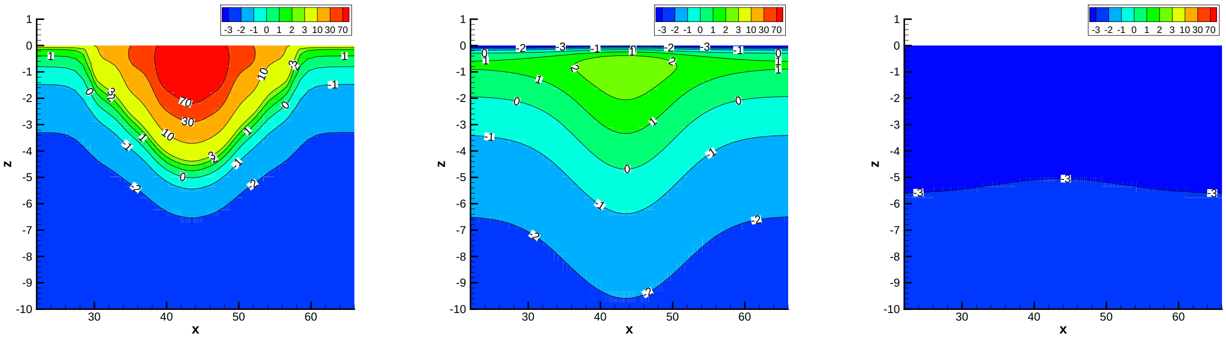
3 Numerical Results

The developed mathematical model allows to take into account the most significant physical and climatic factors influencing on formation of temperature fields in permafrost during operation of flare system [14]. The algorithm used to determination of annual changing of upper boundary parameters allows to decrease amount of initial data and to expect the program code to be presented in remote and clouds simulations [15]. Also the used approach of splitting and decomposition allows to use distributed and parallel computations and, as a result, essentially increase complexity and detailed elaboration of the objects to be simulated [16]. Implicit method of solution allows to use different scales of time steps in numerical simulation.

Let consider a 3D computational domain with $L_x = 87$m, $L_y = 87$m, $L_z = 40$m. The flare system in in center of the soil surface (fig 1). The flare platform has 3 layers: 0.15 m. of concrete slab, 0.10 m. of breakstone, and 2.10 m. of sand. The permafrost is combined of two different frozen soils. Parameters of soils and riprap layers are presented in table 1. We will compare 4 types of flare system operation mode (table 2). Let assume that the month of starting operation is may.

In figures 4–7 temperature field are shown in section by y axis near the flare platform for different operating modes. In figures 8 and 9 annual temperature changing are presented at the depth of 1m and 3m. In figures 10 and 11 the detalization of temperatures under flare platform are shown for summer and winter. The “ground” line in the figures denotes the natural temerature disribution without influence of flare.

Effect of heating for I operating mode is not too intense, but is permanent, and its influence is presented even at the depth of 3m (fig 8). Operating mode II is obviously has a significant effect on the temperature distribution under the flare platform, the deepest soil thawing is observed in this mode (fig 5). When the flare heated for a month (operating mode III), despite the fact that high peak temperature is observed (fig 9), but significant period of rest allows ground to be cooled up to near background values of temperature (fig 10 and



june october march

Figure 6: III operating mode. Temperature field under flare platform on june, october, and march.

Table 2: Types of flare system operatng mode

	time in action	periodicity
I operating mode	1 hour	6 days
II operating mode	24 hours	6 days
III operating mode	1 month	12 years
IV operating mode	1 month	6 months

fig 11). Moreover, heating in the same type cyclically (every 6 months, operating mode IV) has no a significant thermal trace in the soil temperature (fig 7).

4 Conclusion

On the base of a mathematical model of thermal field in a nonuniform frozen soil from a heat source located on the surface of the ground, a horizontal flare system used to gas flaring in northern oil and gas fields is simulated. Forecasts of permafrost degradation around this system is obtained for different operating modes. The purpose of simulations is making recommendations on the optimal choice of the structure of heat-insulating riprap layers to reduce the thermal effects on the permafrost. By computer simulation an acceptable depth is determined, which may be used for heat insulating materials with limited operating temperature range (e.g., for penoplex the temperature has to be no greater than 70^{o}C). Also the features of thermal field propagation in the soil are considered in detail, taking into account different physical and climatic factors. Operating modes, when the flare platform time could be possible to cool down without heat accumulation, are preferable.

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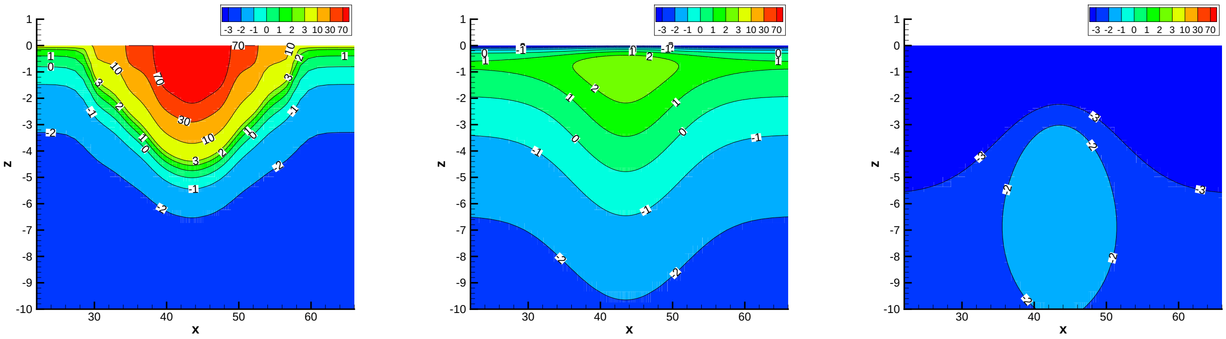
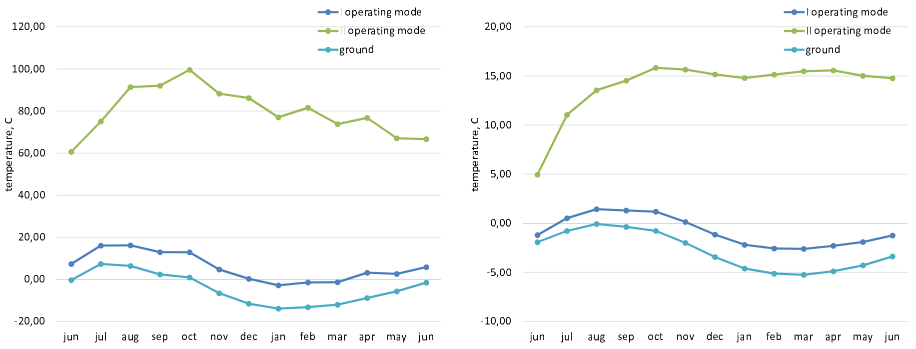


june

october

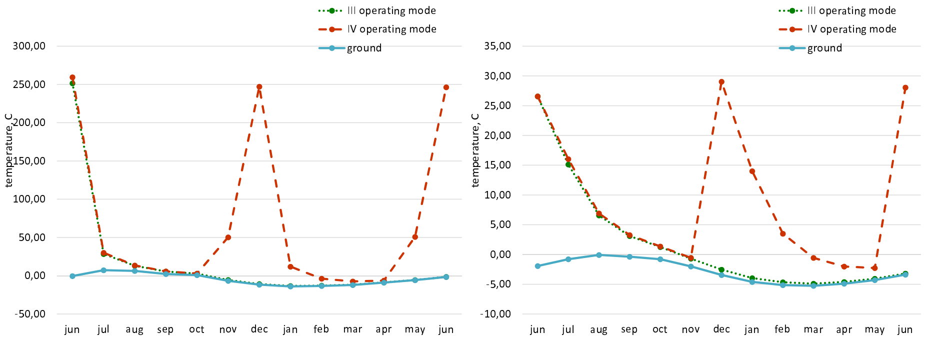
march

Figure 7: IV operating mode. Temperature field under flare platform on june, october, and march.



(depth is 1 m) (depth is 3 m)

Figure 8: I and II operating mode. Temperature changes under flare platform.



(depth is 1 m) (depth is 3 m)

Figure 9: III and IV operating mode. Temperature changes under flare platform.

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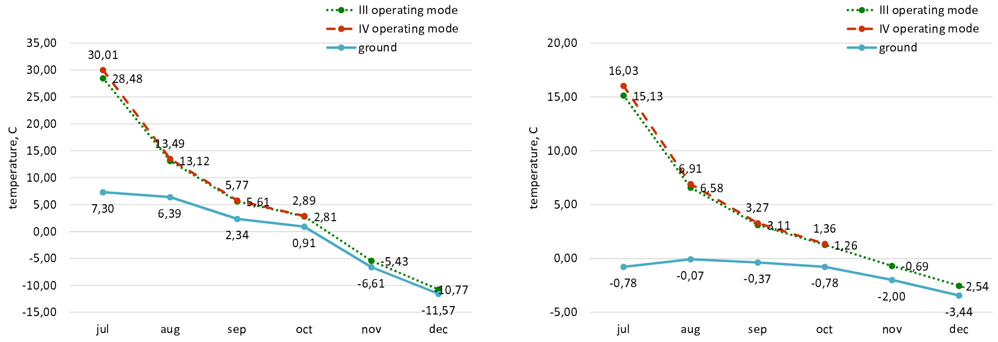

(depth is 1 m) (depth is 3 m)

Figure 10: III and IV operating mode. Temperature changes under flare platform on summer.

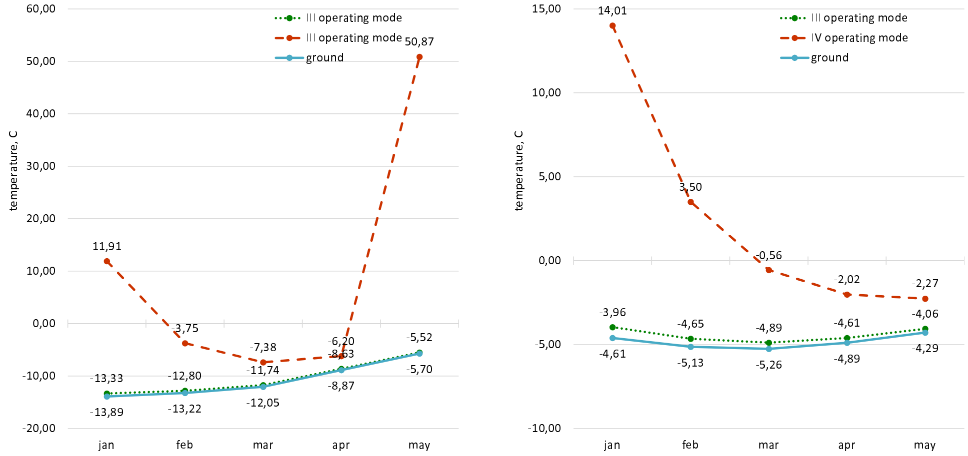

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Figure 11: III and IV operating mode. Temperature changes under flare platform on winter.

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